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Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group

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ABSTRACT

The previously accepted estimates for the areal extent (200,000 km^2) and volume (325,000 to 382,000 km^3) of the Columbia River Basalt Group (CRBG) have, upon reevaluation, been found to be too large. New area and volume estimates for 38 units that compose most of the CRBG indicate that it once covered an area of approximately 163,700 $\pm$ 5,000 km^2 and has a volume of approximately 174,300 $\pm$ 31,000 km^3. Our work further suggests that the volume of individual flows is huge, on average exceeding hundreds of cubic kilometers. The maximum known volume of an individual flow exceeds 2,000 km^3, and some flows may have volumes on the order of 3,000 km^3. Typically such huge-volume flows (here termed "great flows") were able to travel hundreds of kilometers from their vents, with some flows known to have advanced more than 750 km. The eruption of great flows generally ceased with the end of Wanapum volcanism. The extent and volume of great flows qualifies them as the largest known terrestrial lava flows.

INTRODUCTION

Since the late 1960s, many estimates of the area and volume of the Columbia River Basalt Group (CRBG) have been reported in the literature. Initially such estimates were used to demonstrate that large volumes of basaltic lava could be erupted over a short geologic time span and that such eruptive activity may be triggered by extraordinary tectonic events or conditions (e.g., Waters, 1962; Kuno, 1969). Intensive study of the CRBG over the last 20 years has enabled workers to revise the earlier estimates of its extent and volume and also to estimate the volume of individual CRBG units or flows (e.g., Swanson and others, 1975; Swanson and Wright, 1981; Reidel and others, 1982; Beeson and others, 1985).

These estimates have been increasingly employed as important physical constraints on a wide range of problems pertaining to the origin and emplacement history of the CRBG. These problems include modeling of flow-emplacement dynamics (e.g., Shaw and Swanson, 1970a; Mangan and others, 1986; Reidel and Fecht, 1987), magma supply and eruption rates (e.g., Swanson and others, 1975; Wright and Helz, 1981; Reidel and Fecht, 1987), the petrogenesis of CRBG magma (e.g., Wright and others, 1973, 1989; Reidel, 1978, 1983; Hooper, 1984; Carlson,

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1984; Reidel and Fecht, 1987), and regional tectonic models (e.g., Davis, 1981; Reidel, 1984; Reidel and others, this volume).

The importance of reliable estimates of the area and volume of the CRBG, and of its individual units, in addressing these problems is clearly evident. We have discovered that previous estimates of the area and volume of the CRBG are erroneously large. To rectify the problem, we calculated new area and volume estimates for 38 stratigraphic units that compose the CRBG, based on published and unpublished data. We here report the results of this work and discuss how they have led us to reexamine previous concepts concerning the physical size of CRBG flows.

BACKGROUND

Introduction

It would seem logical that the origin of the erroneous area and volume estimates for the CRBG could presumably be traced back to some miscalculation or incorrect assumption, but this is not simply the case. Instead we discovered a more complex story that turns on a forgotten distribution map and subsequent misplaced assumptions concerning the source of the area and volume estimates. In the following section we will briefly trace the evolution of these estimates, from what were once valid estimates to what are now erroneous overestimates.

Recognition of a problem

Recognition that the area and volume estimates were much too large indirectly came to light in September 1985. It was discovered by two of the authors (Tolan and Reidel) while they were reviewing volume estimates for the Frenchman Springs Member that they had recently calculated for another paper (Beeson and others, 1985).

The method they employed to calculate the area of the Frenchman Springs units was based on the proportion of the total area of the CRBG (assumed to be approximately 200,000 km^2) that the unit covered. Their systematic review of previous calculations revealed no errors, but intuitively these values still seemed too great. The only remaining source that might introduce error was the basic assumption of the area of the CRBG. To check this assumption, the area of the CRBG portrayed by Waters (1961, p. 584) was calculated, and the result was approximately 130,000 km^2, not the widely accepted 200,000 km^2 value. Therefore, the area and volume estimates for the Frenchman Springs Member were indeed too large because of the erroneous 200,000 km^2 area of the CRBG.

Origin of the erroneous estimates

On finding that the generally accepted and widely cited areal extent and volume estimates for the CRBG were in error, we questioned how they were originally derived and why errors of such magnitude eluded detection for so long. We reviewed the literature that we had often cited as the source of the estimates. Table 1 is a compilation of the area and volume estimates for the CRBG that we found, or failed to find, in these often cited papers.

The results of this review led us to estimates made by Aaron C. Waters in 1967 that were modified and published by Kuno (1969; Table 1). Kuno (1969) is apparently the original source of the 200,000-km^3 volume estimate and is indirectly responsible for the 200,000-km^2 area estimate as well. Kuno (1969, p. 499) derived his estimate by modifying Waters' estimates for the CRBG. Quoting from Kuno (1969, p. 499):

> "According to Waters (1962) (personal communication, 1967) the total volume of the Columbia River basalts is about 195,000 km^3. On the other hand, Kuno's estimate of the total volume, calculated from the area covered by the lavas (Table 1) and assuming the average thickness of the lava pile to be 1 km, is 220,000 km^3. Thus 200,000 km^3 would be a reasonable estimate."

Clearly, Kuno's volume estimate was derived by taking Waters' area estimate, multiplying by the 1-km average CRBG thickness, and then rounding this number down. Based on Kuno's estimates, one could also conclude that 200,000 km^2 was a "reasonable estimate" of the area of the CRBG.

At this point we thought that we had traced the origin of the erroneous estimates back to A. C. Waters. Although Kuno (1969) presented no CRBG distribution map, we assumed that Waters' estimates were derived from the distribution map presented in an earlier paper (Waters, 1961, p. 584). In discussing this matter with A. C. Waters (personal communication, 1985–1986), however, we learned that this assumption was incorrect.

The estimates provided to Kuno in 1967 by Waters were not based on his 1961 version of the CRBG distribution, but instead were made from a map that greatly expanded the area of the CRBG into portions of central and southeastern Oregon and western Idaho. The expansion of the area of the CRBG was based on preliminary results of then on-going field work, which suggested that some, if not all, of the Miocene basalt in these areas might be part of the CRBG. Therefore the area and volume estimates provided to Kuno in 1967 were based on Waters' then current understanding of the distribution of the CRBG. Apparently a draft version of this distribution map was made but unfortunately not publsihed by Kuno (1969). This failure to clearly link the Waters/Kuno estimates with Waters' expanded CRBG distribution map was a critical oversight that had lasting ramifications.

In the early 1970s, additional field work in Oregon and Idaho convinced Waters that his earlier conclusion about the area of the CRBG (Waters, 1955a, 1961) was basically correct. The expanded CRBG distribution map, which served as the basis for the volume and area estimates in Kuno (1969), was discarded and, unfortunately, soon forgotten as well (A. C. Waters, personal communication, 1986).

After publication of Kuno's paper, the estimates of 200,000 km^2 and 200,000 km^3 began to appear together, or separately, in other papers (e.g., Shaw and Swanson, 1970a; Baksi and Wat-

TABLE 1. REVIEW OF COMMONLY CITED SOURCES FOR THE 200,000 km^2 AND 200,000 km^3 ESTIMATES FOR THE AREAL EXTENT OF THE CRBG

Author	Reported Estimate of Area/Volume	Comments
Waters (1955a)	100,000 mi^2 (258,985 km^2)/ 35,000 mi^3 (145,874 km^3)	Included portions of Owyhee basalts later excluded from the CRBG.
Waters (1955b)	None/None	Occasionally cited as reporting estimates of these values.
Waters (1961)	None/None	Often cited as reporting estimates of these values. This paper presents map of the CRB (p. 584) later used by Swanson and others (1979b) with only minor modification.
Waters (1962)	None/ 43,000 mi^3 (179,217 km^3)	Volume estimate presented in Figure 2 (p. 160). Also presents volume estimate of the "Yakima basalt-type": 30,000 mi^3 (125,035 km^3) (p. 162).
Waters (1967, *in* Kuno, 1969)	220,000 km^2/ 195,000 km^3	Personal communication to Kuno. Estimates reported in Table 1 (p. 496).
Kuno (1969)	220,000 km^2/ 200,000 km^3	Assumed average thickness of CRB to be 1 km and estimated CRBG volume to be 220,000 km^3. This differed from Waters' estimates in his Table 1 (p. 496). Kuno decided a "reasonable" estimate was 20,000 km^3 (p. 499).
Kienle (1971)	80,000 mi^2 (207,188 km^3)/ None	

kins, 1973; Swanson and others, 1975; Bentley, 1977). Only rarely did authors (e.g., Shaw and Swanson, 1970a) correctly attribute the origin of the estimates to Kuno (1969). During this period, Waters' (1961) CRBG distribution map, with minor modifications, began to be cited and reproduced by other authors (e.g., Walker, 1970; Wright and others, 1973; Swanson and others, 1975). The implied tie between Waters' (1961) CRBG distribution map and the volume and area estimates of Kuno (1969) was thus established (e.g., Shaw and Swanson, 1970a; Swanson and others, 1975) and subsequently reinforced by continued use of these values. The erroneous 200,000-km^2 area estimate also caused the volume of the CRBG to be greatly overestimated. For example, Reidel and others' (1982) use of the erroneous area estimate resulted in their overestimate of the volume of the Grande Ronde Basalt. This in turn led them to place the total volume of the CRBG at 325,000 km^3. Similar errors by Beeson and others (1985), as discussed above, helped boost the estimated volume of the CRBG to more than 382,000 km^3 before the error was detected.

Methodology employed to produce new area and volume estimates

After reviewing available data, we determined that new and more reliable area and volume estimates for 38 stratigraphic units within the CRBG (Fig. 1) could be made. For each unit, we compiled a new 1:1,000,000 scale map (Table 2) of its inferred original distribution. Thickness data for each unit, compiled from both published literature and unpublished data supplied by the authors, were added to the maps during the compilation process. All known vents or dikes for each unit were added to the base map.

Each resulting map was digitized into computer files that could be manipulated by the Interactive Surface Modeling (ISM™) software package (Dynamic Graphics, Inc., Berkeley, California). Using ISM™, the area of each unit was calculated and an isopach map was generated. The isopach maps were reviewed and modified by the authors. The volume of each unit was calculated from the revised isopach maps by ISM™. The volume calculation was then verified by either a simplified grid-square summation routine within ISM™, hand-calculating the volume from the isopach map, or both.

The area of the five formal CRBG formations, and subsequently the entire CRBG, was defined by sequentially stacking all the individual units to produce a composite map. The outermost margin of each formation was digitized, and the area contained within the resulting polygon determined by ISM™. The total volume of the formations was derived by summing the totals for individual units used to produce the maps.

DISCUSSION OF RESULTS

Distribution maps of the CRBG units

The CRBG distribution maps produced by our work (Fig. 2) are an updated and expanded version of a series of distribution

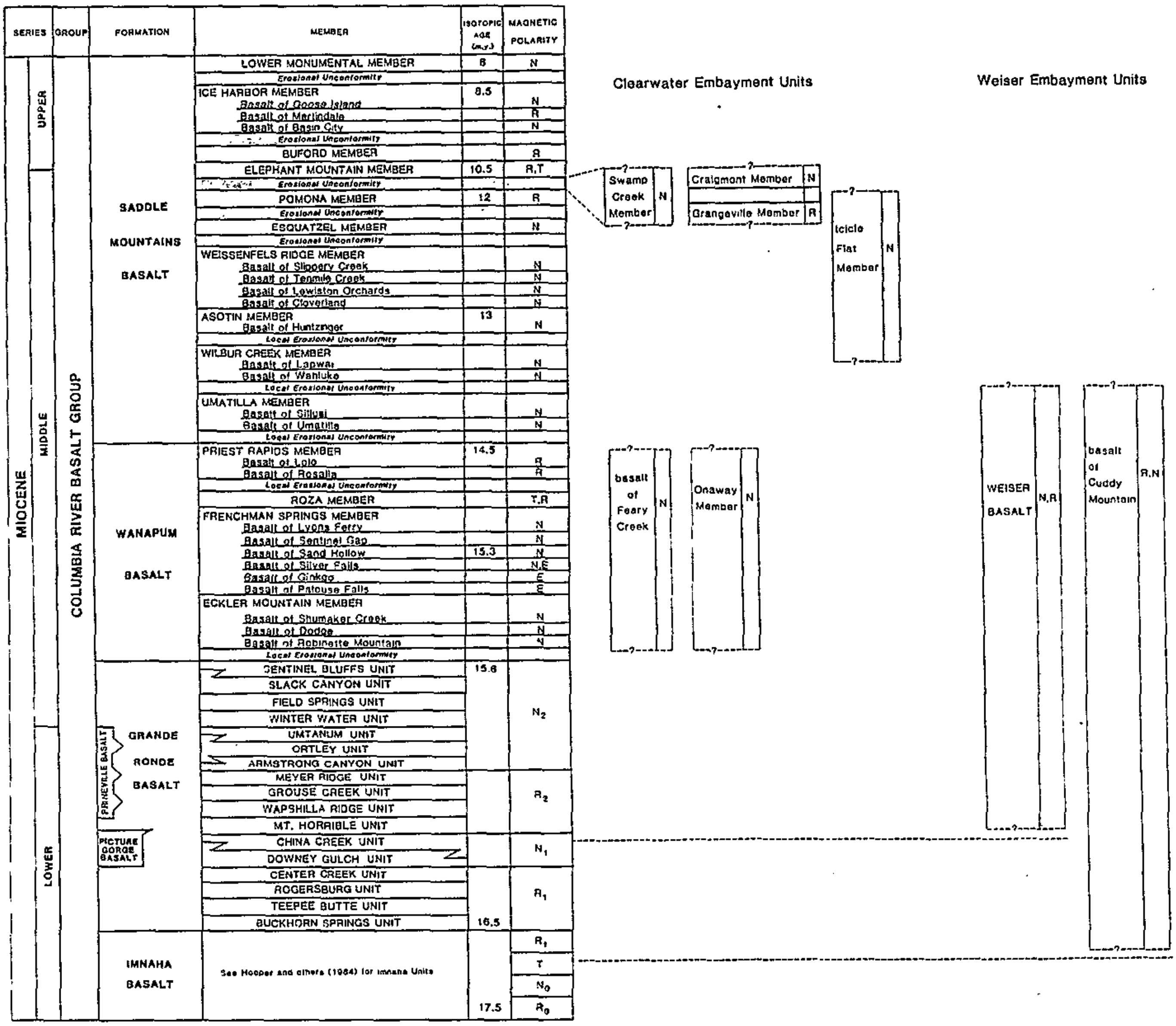


Figure 1. Nomenclature and stratigraphic relations of Columbia River Basalt Group units. Main body of chart adapted and modified from Swanson and others (1979b), Beeson and others (1985), and Reidel and Fecht (1987). Some informal units from Clearwater embayment (Camp, 1981) have been integrated into the main body of the chart (e.g., basalt of Lapwai; Hooper, 1985; Reidel and Fecht, 1987) based on recent work that clarified their stratigraphic relations to other formal CRBG units. Stratigraphic position of Prineville basalt based on data from Anderson (1978, 1980, unpublished data), Beeson and Moran (1979), Swanson and others (1979a, b), Smith (1986), and Reidel and Tolan (unpublished data). Stratigraphic relations of most informal units in Clearwater (Camp and others, 1982) and Weiser (Fitzgerald, 1984) embayments to the five formal CRBG formations is less certain and are depicted on right side of figure. Isotopic ages are from McKee and others (1977, 1981), Long and Duncan (1983), Beeson and others (1985), and unpublished data from the authors. N, normal magnetic polarity; R, reversed magnetic polarity; T, transitional magnetic polarity; E, excursional magnetic polarity.

maps originally presented in Swanson and others (1979b, Plate 1). As the result of the field work done since 1977 when the original maps were made, most of the unit distribution maps presented in Figure 2 have changed from their original portrayal. Table 2 provides a brief summary of the major changes that have been made.

Vents and dikes of the CRBG. CRBG flows were erupted from NNW-trending linear fissure systems, ranging from tens to hundreds of kilometers in length, generally found in the eastern part of the Columbia Plateau (Waters, 1961; Taubeneck, 1970; Swanson and others, 1975, 1979a, b, 1980, 1981; Swanson and Wright, 1981; Hooper and Swanson, 1987). Erosion has revealed the dikes that mark the remains of the linear fissure systems and, less commonly, the small pumice and spatter cones marking local vents. Much field and laboratory work over the past several decades has succeeded in sorting out which CRBG units many of these dikes fed. Those unit-identified vents and dikes are shown schematically on the distribution maps (Fig. 2), but collectively they represent a relatively small fraction of the total number of known dikes and vents (e.g., see Swanson and others, 1979a, 1980, 1981). Most mapped dikes have been identified down to formational level only, precluding their inclusion on our unit distribution maps. This creates the illusion that relatively few sources for the CRBG flows are known, when quite the opposite is true.

Figure 3 presents a compilation of known CRBG vents and dikes from available mapping and gives a better indication of the overall number and distribution of these features than Figure 2. Most of the dikes and vents in Figure 3 have been assigned to either the Monument or Chief Joseph dike swarms.

The Monument dike swarm contains vents and dikes for flows of the Picture Gorge Basalt. Regional reconnaissance mapping (Swanson and others, 1981) of the northern end of the Monument dike swarm indicated that both Grande Ronde and Picture Gorge vents and dikes were present. More detailed examinations of these "Grande Ronde" vents and dikes by Reidel and Tolan (unpublished data) and later by Bailey (this volume) show these features to be sources for Dayville flows (Picture Gorge Basalt) only.

Uplift and erosion in the southeastern part of the Plateau have exposed vents and dikes that fed Imnaha, Grande Ronde, Wanapum, and Saddle Mountains flows. This great concentration of vents and dikes was originally divided into the Grande Ronde and Cornucopia dike swarms (Waters, 1961; Lindgren, 1901). Taubeneck (1970) found no discernible break between these two swarms and merged them into a single great swarm that he called the Chief Joseph dike swarm. Reputedly more CRBG vents and dikes are known within the Chief Joseph swarm than are shown on existing maps and in Figure 3. For example, Taubeneck (1970, p. 80) reports that between 1,700 and 2,100 dikes are exposed in the Wallowa Mountains area of northeastern Oregon, but no maps show these dikes.

The western and northern boundaries of the Chief Joseph dike swarm are not clearly evident and are open to debate. Past boundaries for this swarm have been located where the number of dikes diminish (e.g., Waters, 1961; Taubeneck, 1970). Others (e.g., Swanson and others, 1975; Camp and others, 1982) have suggested that the decrease in abundance of dikes may simply be due to the lack of exposures deep enough to reveal feeders for Grande Ronde and Wanapum flows. They further argue that distributional patterns for a number of units (e.g., N_2 Grande Ronde Basalt, Frenchman Springs Member, Priest Rapids Member; Fig. 2) imply that feeder dikes must lie within the central and/or northern parts of the Columbia Plateau. Our revised unit distribution maps (Fig. 2) support this contention.

Within the Chief Joseph dike swarm, there is no strict geographic segregation of Imnaha, Grande Ronde, Wanapum, and Saddle Mountains vents and dikes (Swanson and Wright, 1978; Hooper and Swanson, 1987). However, the distribution of individual units within the Grande Ronde and Wanapum Basalts suggest some small changes in the location of eruptive activity over time. The distribution maps of the four Grande Ronde magnetostratigraphic units (Fig. 2) suggest that eruptive activity associated with the Grande Ronde Basalt died out in the southern portion of the Chief Joseph dike swarm by R_2 time. Subsequent eruptive activity associated with the Wanapum Basalt also seems to have been located along the central and northern portions of the Chief Joseph dike swarm (Fig. 2). Within the Wanapum Basalt, the locations of vents and dikes of Frenchman Springs, Roza, and Priest Rapids Members (Fig. 2) generally show a progressive shift from west to east (Hooper and Swanson, 1987). Eruptive activity that produced the Saddle Mountains members (Fig. 2) appears to have been loosely concentrated along the central portion of the Chief Joseph dike swarm.

New area and volume estimates for the CRBG

Table 3 summarizes our new estimates of the areal extent and volume of units of the CRBG. Overall, the most significant change is the reduction of the total area and volume of the CRBG. Our new estimates reduce the overall area of the CRBG from 200,000 km^2 to about 163,700 km^2, a reduction of over 18 percent. More dramatic is the reduction in the volume of the CRBG, which went from the previous high of 382,000 km^3 to about 174,300 km^3, a net decrease of over 50 percent.

The percentage of the total volume of the CRBG that each of the five formations represents also changed. The Imnaha, Picture Gorge, and Wanapum Basalts are volumetrically smaller than previously estimated (Swanson and Wright, 1979). The Grande Ronde Basalt still constitutes most of the CRBG (Table 3), with the other formations together totalling less than 15 volume percent (Fig. 4).

Uncertainties associated with the area and volume estimates. Uncertainty or error in the area and volume estimates presented in Table 3 can come from three basic sources: (1) accuracy of the estimate of the original extent of each unit, (2) the number, distribution, and accuracy of thickness determinations for each unit, and (3) the method employed to calculate the area

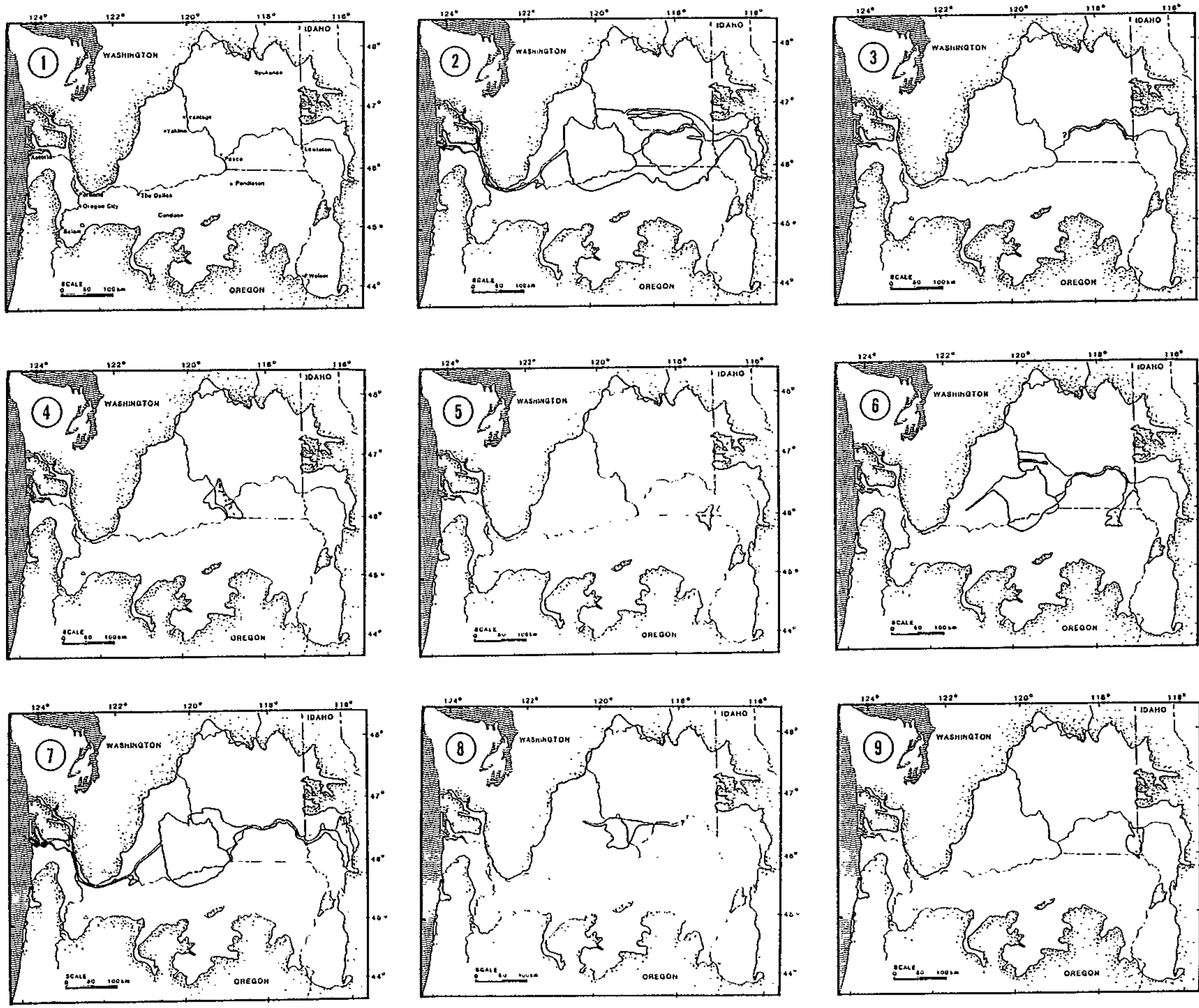
TABLE 2. A SUMMARY OF SIGNIFICANT REVISIONS MADE TO DISTRIBUTION MAPS OF CRBG UNITS PRESENTED IN FIGURE 2

Unit	Revisions
CRBG (composite)	Expansion of areal extent of CRBG in western Oregon/Washington (Beeson and Tolan, unpublished mapping); inclusion of Snavely and others (1973) Miocene coastal basalts into CRBG; addition of Prineville basalt in north-central Oregon; expansion of CRBG distribution in western Idaho/ northeastern Oregon based on mapping by Swanson and others (1981) and Fitzgerald (1984).
Saddle Mountains Basalt (composite)	Revised westernmost extent of Saddle Mountains Basalt; added Snavely and others (1973) basalt of Packsack Lookout to Saddle Mountains Basalt; changed location of Saddle Mountains pathway through western plateau and Columbia Gorge region based on mapping by Anderson (1980) and Tolan and Beeson (1984).
Lower Monumental Memter	No significant changes.
Ice Harbor Member	No significant changes.
Buford Member	Expansion of distribution based on mapping of Hooper (*in* Swanson and others, 1981) and Stoffel (1984).
Elephant Mountain Member	Expansion of western extent of unit based upon mapping of Bentley and others (1980). Revised central Plateau after Reidel (1984).
Pomona Member	Revised western extent of unit based upon mapping of Anderson (1980; 1987) and Tolan and Beeson (1984); inclusion of Snavely and others (1973) basalt of Packsack Lookout in coastal areas to this unit. Expansion of distribution in Idaho based upon mapping by Camp (*in* Swanson and others (1979a; 1981). Revised central Plateau after Reidel (1984).
Esquatzel Member	No significant changes.
Weissenfels Ridge Member	Expansion of northern extent of unit based upon mapping by Hooper and others (1985).
Asotin Member	Expansion of eastern extent of unit based upon mapping by Camp (*in* Swanson and others, 1981) and Hooper and others (1985); revised extent of unit in Pasco Basin after Reidel and Fecht (1987).
Wilbur Creek Member	Expansion of southern extent of unit based upon mapping by Hooper and others (1985); revised extent of unit in Pasco Basin after Reidel and Fecht (1987).
Umatilla Member	No significant changes.
Wanapum Basalt (composite)	Revised distribution in western Oregon based upon unpublished mapping by Beeson and Tolan; inclusion of Snavely and others (1973) Cape Foulweather flows into this unit. Distribution revised in the western Plateau region based on mapping of Swanson and others (1979a; 1981).
Priest Rapids Member	Revision of distribution in western Plateau based upon mapping of Swanson and others (1981) and Anderson (1987); revision of unit distribution in Cascades and western Oregon from Vogt (1981), Tolan and Beeson (1984), and Anderson and Vogt (1987). Revised central Plateau after Reidel (1984).
Roza Member	No significant changes.
Frenchman Springs Member (composite)	Revision of distribution in western Oregon after Beeson and others (1985); inclusion of Cape Foulweather flows of Snavely and others (1973) in this unit.
basalt of Lyons Ferry	No significant changes from Beeson and others (1985).
basalt of Sentinel Gap	No significant changes from Beeson and others (1985).
basalt of Sand Hollow	No significant changes from Beeson and others (1985).
basalt of Silver Falls	No significant changes from Beeson and others (1985).
basalt of Ginkgo	No significant changes from Beeson and others (1985).
basalt of Palouse Falls	No significant changes from Beeson and others (1985).
Eckler Mountain Member	Expansion of distribution based on mapping of Swanson and others (1980; 1981).

TABLE 2. A SUMMARY OF SIGNIFICANT REVISIONS MADE TO DISTRIBUTION MAPS OF CRBG UNITS PRESENTED IN FIGURE 2

Unit	Revisions
Grande Ronde Basalt (composite)	Revision and expansion of distribution in western Oregon based upon unpublished mapping of Beeson and Tolan; inclusion of Snavely and others (1973) Depoe Bay flows in coastal areas of Washington and Oregon; exclusion of Prineville flows from this unit.
N_2 Grande Ronde Basalt	New map.
R_2 Grande Ronde Basalt	New map.
N_1 Grande Ronde Basalt	New map.
R_1 Grande Ronde Basalt	New map.
Prineville basalt	New map.
Picture Gorge Basalt	Minor expansion of the northern extent based on mapping by Swanson and others (1981) and Bailey (1986).
Imnaha Basalt	Southern extent expanded based on mapping by Hooper and Camp (*in* Swanson and others, 1981) and Fitzgerald (1984).
Craigmont member	No significant changes from Camp and others (1982).
Swamp Creek member	No significant changes from Camp and others (1982).
Grangeville member	No significant changes from Camp and others (1982).
Icicle Flat member	No significant changes from Camp and others (1982).
basalt of Feary Creek	No significant changes from Camp and others (1982).
Onaway member	No significant changes from Camp and others (1982).
Weiser basalt	No significant changes from Fitzgerald (1984).
basalt of Cuddy Mountain	No significant changes from Fitzgerald (1984).

Figure 2 (following 4 pages). Maps showing inferred original extent of units in Columbia River Basalt Group. Question marks denote uncertainty as to location of a unit's margin. Thin solid lines schematically show locations of known feeder dikes; "x" denotes location of specific vents. See Table 2 for list of data sources used to compile these maps: (1) entire CRBG; (2) Saddle Mountains Basalt; (3) Lower Monumental Member, (4) Ice Harbor Member, (5) Buford Member, (6) Elephant Mountain Member, (7) Pomona Member, (8) Esquatzel Member, (9) Weissenfels Ridge Member, (10) Asotin Member, (11) Wilbur Creek Member, (12) Umatilla Member, (13) Wanapum Basalt, (14) Priest Rapids Member, (15) Roza Member, (16) Frenchman Springs Member, (17) basalt of Lyons Ferry, (18) basalt of Sentinel Gap, (19) basalt of Sand Hollow, (20) basalt of Silver Falls, (21) basalt of Ginkgo, (22) basalt of Palouse Falls, (23) Eckler Mountain Member, (24) Grande Ronde Basalt, (25) N_2 Grande Ronde Basalt, (26) R_2 Grande Ronde Basalt, (27) N_1 Grande Ronde Basalt, (28) R_1 Grande Ronde Basalt, (29) Prineville basalt, (30) Picture Gorge Basalt, (31) Imnaha Basalt, (32) Craigmont and Swamp Creek members, (33) Grangeville and Icicle Flat members, (34) basalt of Feary Creek and Onaway member, (35) basalt of Cuddy Mountain and Weiser basalt.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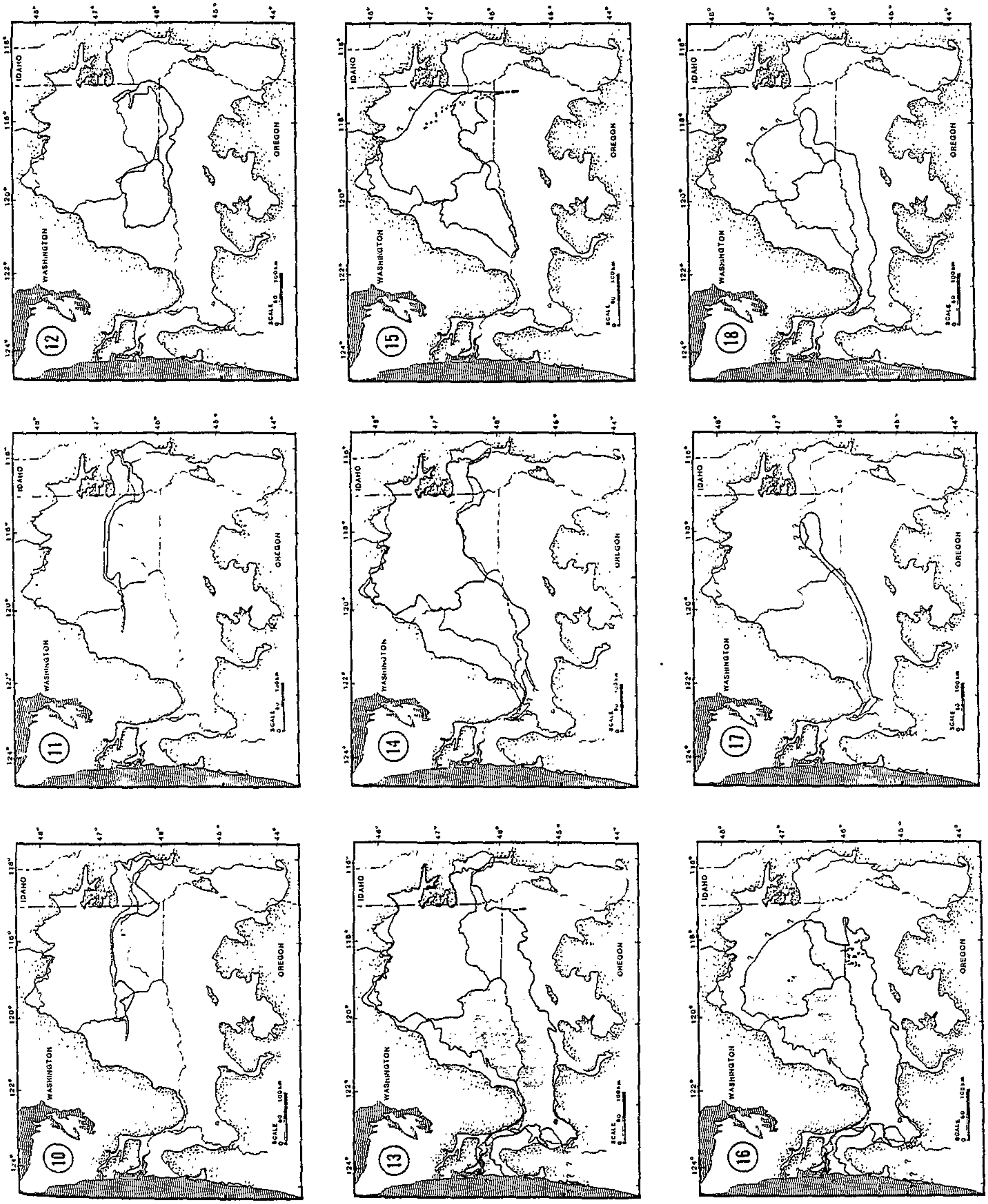
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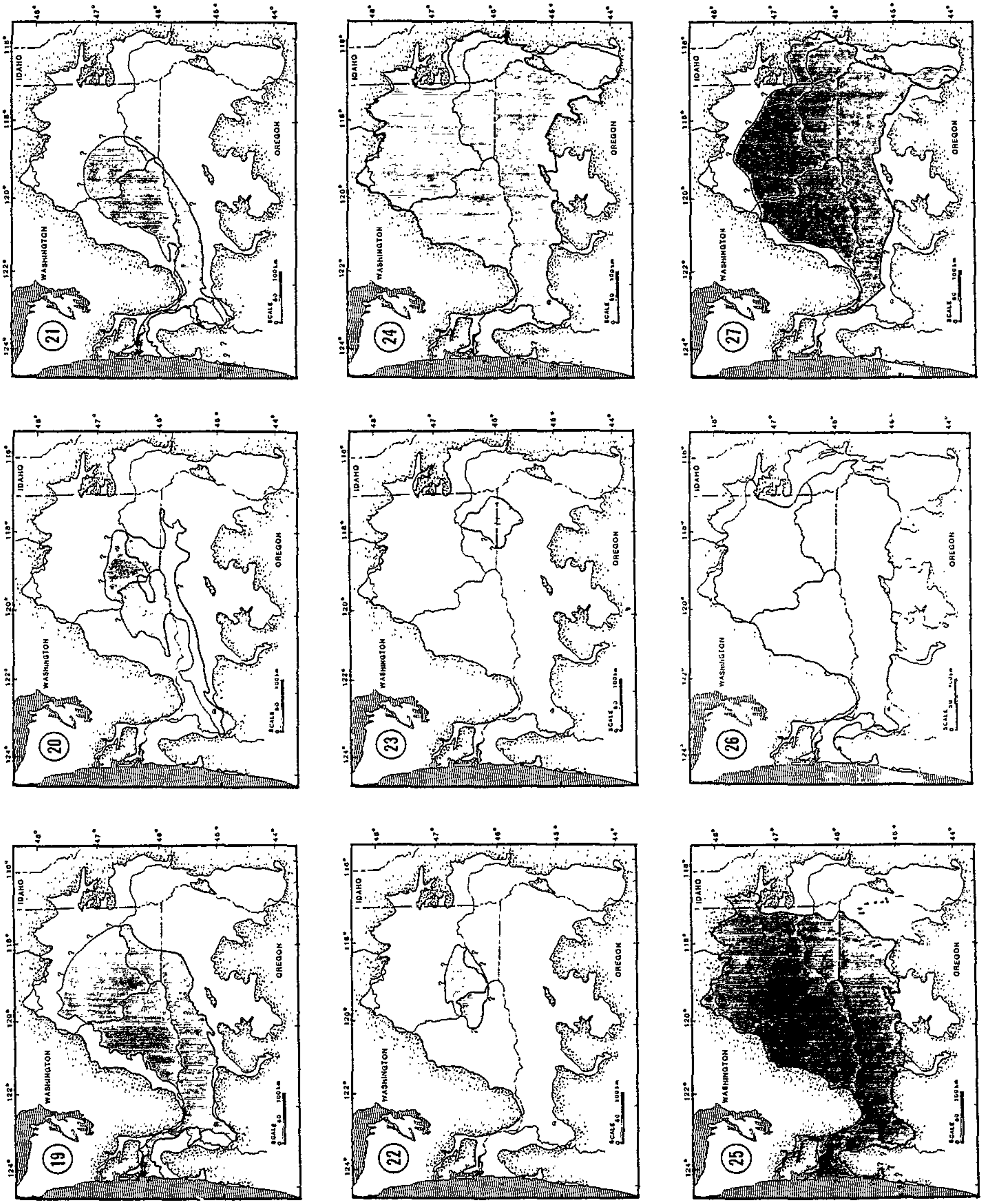
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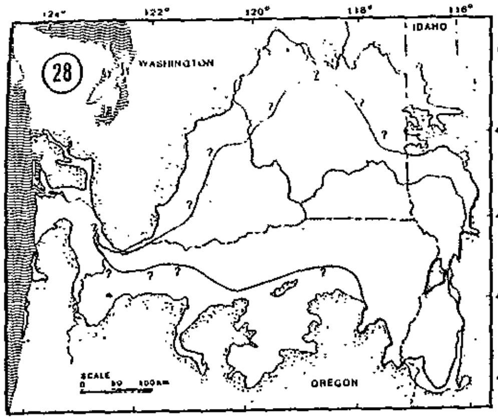
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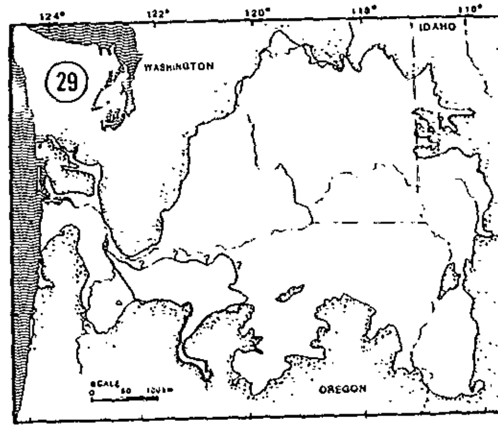
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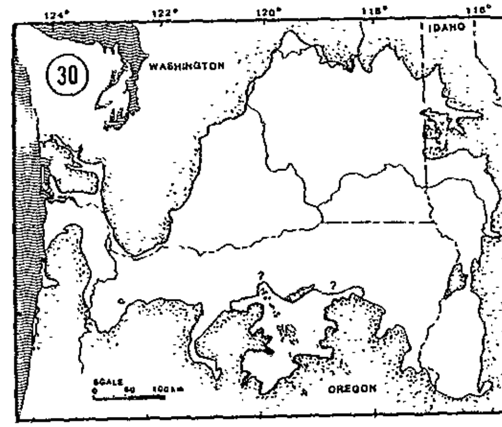
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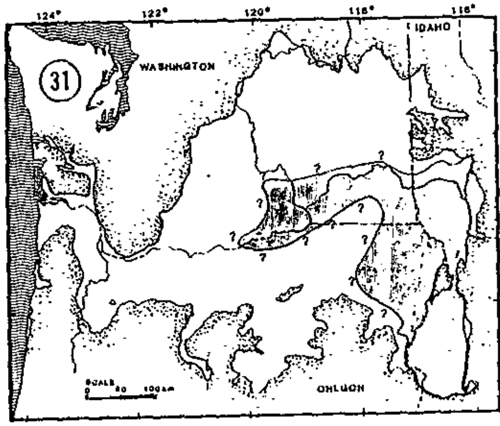
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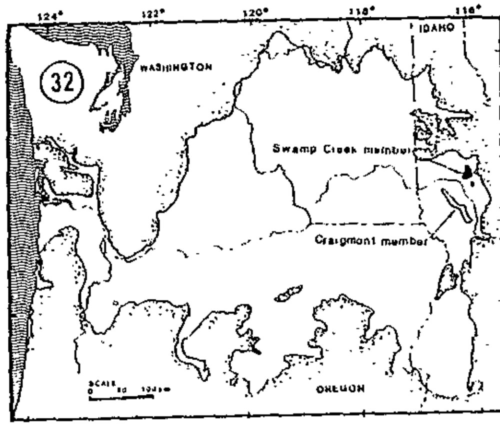
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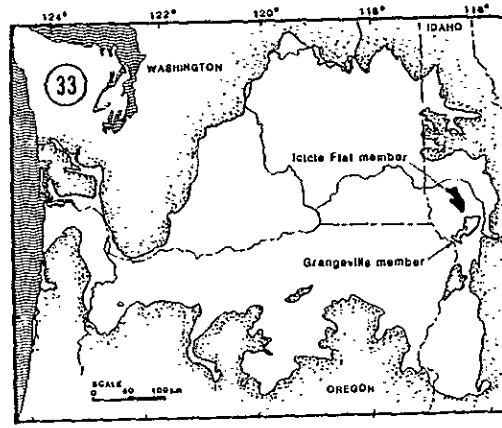
Swamp Creek member
Craigmont member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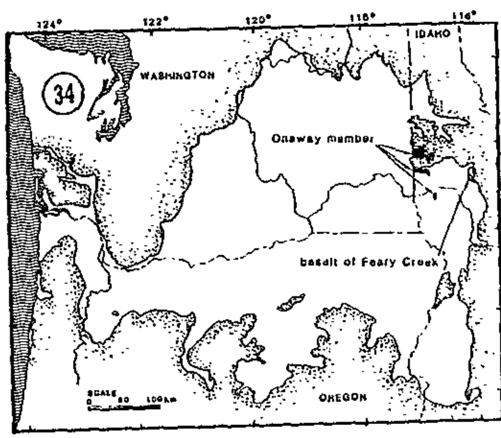
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basalt of Feary Creek
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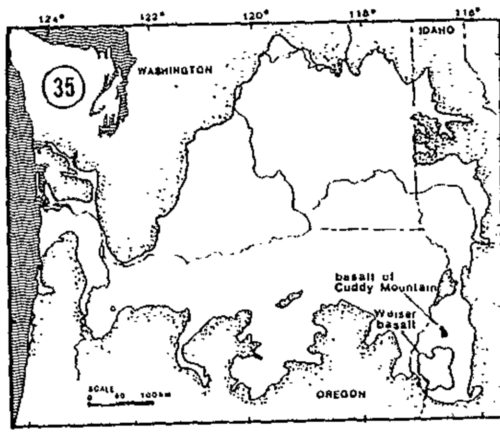
35
WASHINGTON
IDAHO
basalt of
Cuddy Mountain
Weiser
basalt
OREGON

TABLE 3. REVISED ESTIMATES OF THE PHYSICAL DIMENSIONS OF CRBG UNITS*

CRBG Unit	Areal Extent (km^2)	Volume (km^3)	Volume Percent	Est. Number of Flows	Average Volume per Flow (km^3)	Isotopic Age (Ma)
Saddle Mountains Basalt						
Lower Monumental Member	430	15	0.01	1	15	6
Ice Harbor Member	2150	75	0.04	4	19	
Buford Member	580	20	0.01	1	20	
Elephant Mountain Member	13,450	440	0.25	2	220	10.5
Pomona Member	20,550	760	0.44	1	760	12
Esquatzel Member	2710	70	0.04	1	70	
Weissenfels Ridge Member	1210	20	0.01	4	5	
Asotin Member	6440	220	0.13	1	220	
Wilbur Creek Member	3090	70	0.04	2	35	
Umatilla Member	15,110	720	0.41	2	360	
Composite Saddle Mountains	30,570	2410	1.38	19	127	
Wanapum Basalt						
Priest Rapids Member	57,300	2800	1.60	3	933	14.5
Roza Member	40,350	1300	0.74	4	325	
Frenchman Springs Member						
basalt of Lyons Ferry	5900	90	0.05	1	90	
basalt of Sentinel Gap	38,760	1190	0.68	4	297	
basalt of Sand Hollow	67,110	2660	1.52	7	380	15.3
basalt of Silver Falls	28,840	710	0.41	4	177	
basalt of Ginkgo	37,170	1570	0.90	4	392	
basalt of Palouse Falls	8890	190	0.12	1	190	
Composite Frenchman Springs	69,740	6410	3.68	21	305	
Eckler Mountain Member	6090	170	0.10	8	21	
Composite Wanapum	95,950	10,680	6.12	36	297	
Grande Ronde Basalt						
N_2 Grande Ronde Basalt	114,460	27,900	16.00	33	845	15.6
R_2 Grande Ronde Basalt	117,730	53,100	30.46	45	1180	
N_1 Grande Ronde Basalt	102,340	31,400	18.01	15	2093	
R_1 Grande Ronde Basalt	96,650	36,200	20.76	27	1340	16.5
Composite Grande Ronde	149,000	148,600	85.23	120	1238	
Prineville Basalt	11,440	590	0.34	8	74	
Picture Gorge Basalt	10,680	2400	1.38	61	39	
Imnaha basalt	50,200	9500	5.45	26	365	17 - 16.5
Craigmont member	280	6	0.003	1	6	
Swamp Creek member	140	3	0.002	1	3	
Grangeville member	520	11	0.006	1	11	
Icicle Flat member	350	7	0.004	1	7	
basalt of Feary Creek	60	1	0.0005	3	0.33	
Onaway member	370	7	0.004	2	3.5	
basalt of Cuddy Mountain	70	1	0.0005	4	0.25	
Weiser basalt	2130	140	0.080	28	5	
CRBG—TOTALS	163,700	174,356	100	311	561	17 - 6

***Number of flows within units taken from the following sources:**
- Lower Monumental Member—Swanson and others, 1979b
- Ice Harbor Member—Helz, 1978
- Buford Member—Ross, 1978
- Elephant Mountain Member—Swanson and others, 1979b; Reidel and Fecht, 1981
- Pomona Member—Swanson and others, 1979b, 1981
- Esquatzel Member—Swanson and others, 1979b; Reidel and Fecht, 1981
- Weissenfels Ridge Member—Hooper and others, 1985; Reidel and others, 1989
- Asotin Member—Swanson and others, 1979b; Reidel and Fecht, 1987
- Wilbur Creek Member—Swanson and others, 1979b; Reidel and Fecht, 1987
- Umatilla Member—Swanson and others, 1979b; Reidel and Fecht, 1987
- Priest Rapids Member—Swanson and others, 1979b; Reidel and Fecht, 1981
- Roza Member—Martin, 1987
- Frenchman Springs Member—Beeson and others, 1985
- Eckler Mountain Member—Swanson and others, 1979b; Hooper and Swanson, 1989
- Grande Ronde magnetostratigraphic units—Reidel and others, this volume
- Prineville basalt—J. L. Anderson and M. H. Beeson, unpublished data; Smith, 1986
- Picture Gorge Basalt—Bailey, 1986
- Imnaha Basalt—Hooper and others, 1984
- Craigmont, Swamp Creek, Grangeville, Icicle Flat, Onaway members and basalt of Feary Creek—Camp, 1981
- basalt of Cuddy Mountain and Weiser basalt—Fitzgerald, 1984

Sources used to compile isotopic ages:
- Lower Monumental, Elephant Mountain, and Pomona Members—McKee and others, 1977
- Priest Rapids Member—Rockwell Hanford Operations, unpublished data, 1982
- basalt of Sand Hollow—Beeson and others, 1985
- Grande Ronde Basalt—Long and Duncan, 1983
- Imnaha Basalt—McKee and others, 1981

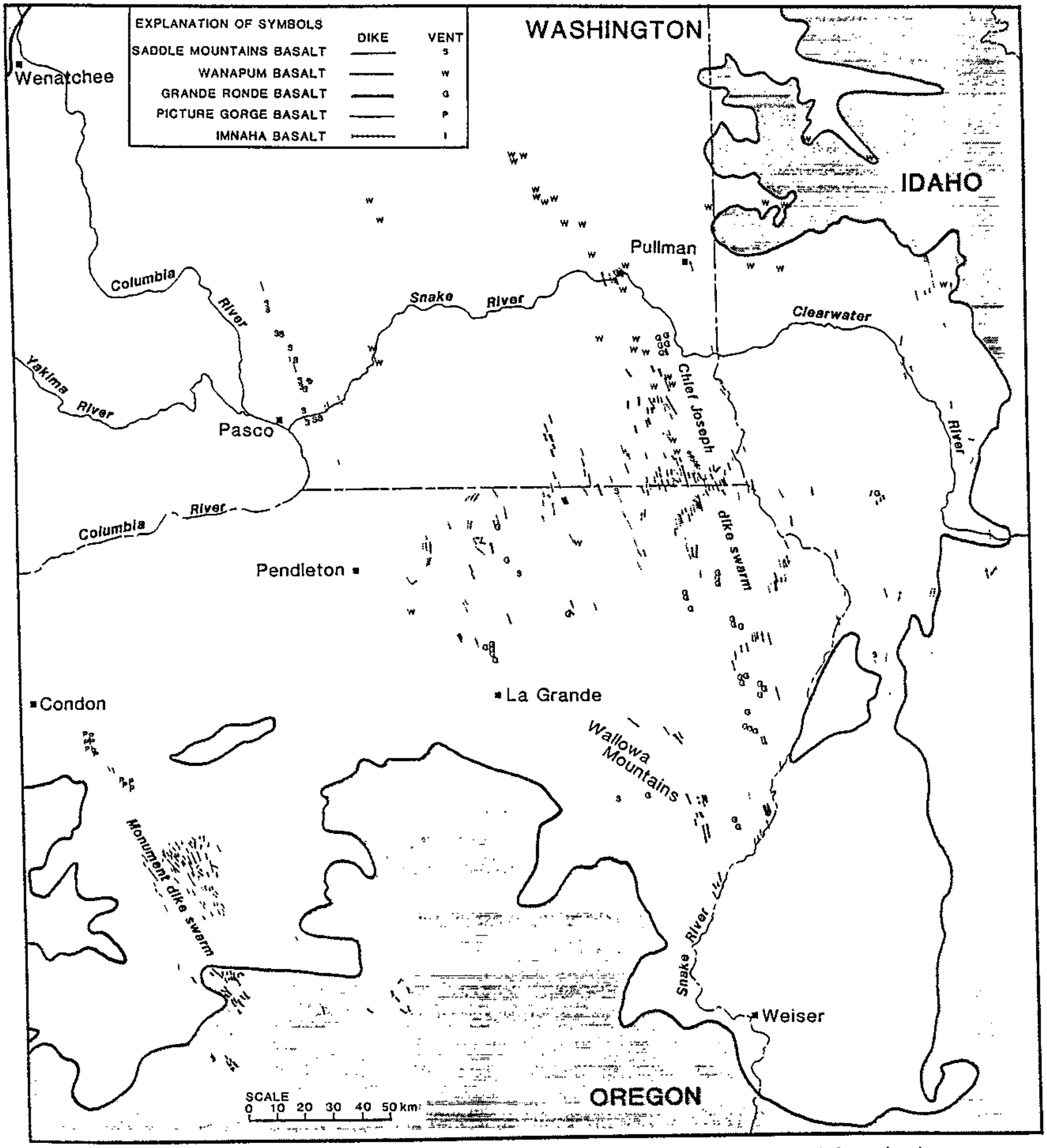

Figure 3. Map showing location of known CRBG vents and dikes. Location and formational designation of vents and dikes compiled from following sources: Barrash and others (1980). Brown and Thayer (1966), Hooper and Webster (1982), Hooper and others (1985), Newcomb (1970), Reidel and others (1989), Robinson (1975), Swanson and others (1979a, 1980, 1981), Wilcox and Fisher (1966).

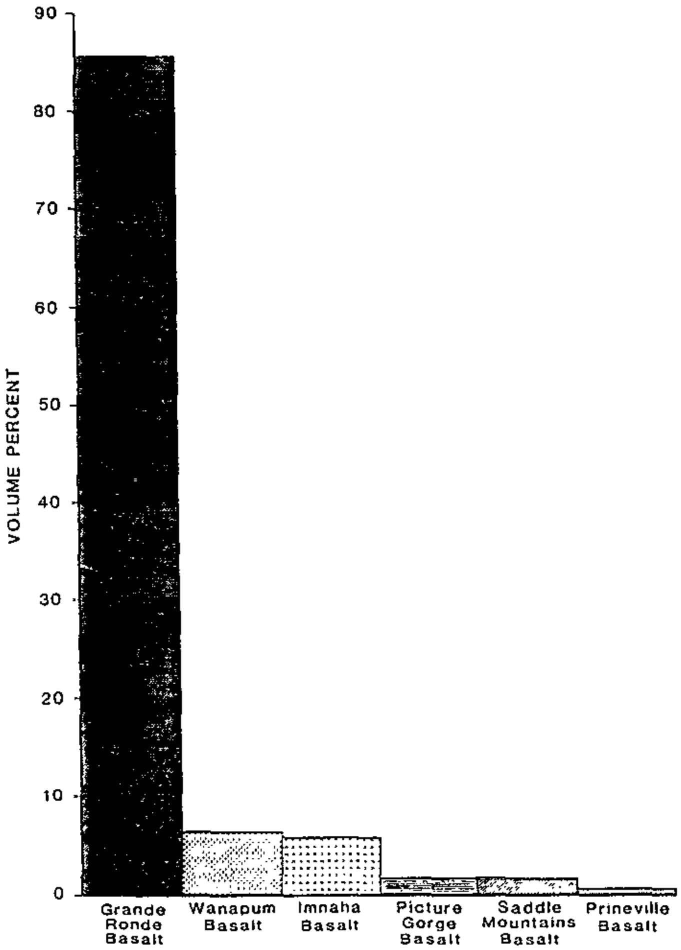

Figure 4. Histogram showing percentage of the total volume of CRBG that each formation represents in descending order of importance. Flows of Prineville chemical type previously considered part of Grande Ronde Basalt (Swanson and others, 1979b) are treated as separate informal unit (Reidel and others, this volume).

and volume for each unit. The first two sources of uncertainty are inherited from the data base used to construct the isopach maps and are the most critical factors in determining the ultimate accuracy. The uncertainties associated with the most extensive and voluminous units (Grande Ronde, Wanapum, and Imnaha Basalts) would have the greatest potential impact. In the following section, we evaluate the uncertainty in the estimates for the three principal formations (Table 4).

Problems encountered during the construction of unit isopach maps are specific to four geographic areas. These area-related problems are: (1) determining the extent and thickness of units that are deeply buried beneath younger units on the Columbia Plateau, (2) defining the degree of erosional stripping around the margins of the units, (3) determining the extent and thickness of invasive CRBG units in the coastal regions of Oregon and Washington, and (4) estimating the distribution and thickness of the offshore portion of the CRBG.

The first problem area has the greatest potential for uncertainty in the volume estimates for the Imnaha and the R_1 and N_1 Grande Ronde Basalts. Defining the extent and thickness of these units was especially difficult because the only direct data on these units were obtained from about a dozen boreholes that either partly or completely penetrated the units. Determining the identity and thickness of units within these boreholes was based on geochemical data from chip and core samples and analysis of geophysical logs. This information was crucial for establishing the presence or absence of the older CRBG units. A discussion of the Grande Ronde Basalt stratigraphy within these boreholes, as well as the criteria we employed to identify the Grande Ronde magnetostratigraphic units in the subsurface, is presented in Reidel and others (this volume).

The borehole data alone do not provide sufficient information on the extent and thickness of these units and consequently were supplemented by "indirect" data on the thickness of the CRBG obtained from seismic refraction, magnetotelluric, and gravity surveys (Rohay and Malone, 1983; Glover, 1985; Berkman and others, 1987; Catchings and Mooney, 1988; U.S. Department of Energy, 1988). Results from these geophysical surveys, when "calibrated" by using actual thickness data from adjacent boreholes, gave us a better basis from which to extrapolate the thickness of the CRBG. This information, combined with available surface and shallow borehole data around the outer margin of the CRBG, were also used to infer the approximate margin of the unit. Margins established in this manner are denoted by a series of question marks on the unit distribution map (Fig. 2). In such cases, all that can be established is that the unit in question pinches out somewhere between the last direct data point and an exposure deep enough to reveal the unit, which in many cases is the outer margin of the CRBG. This uncertainty is the chief basis for establishing the potential error (Table 4) in the area estimates.

We encountered problems with estimating the extent and thickness of units in the coastal regions for several slightly different reasons. The first resulted from the invasive nature of the CRBG units within this region and the fact that complex invasive bodies do not lend themselves to simple volumetric calculations. The complexities of these invasive units have been clearly demonstrated by Snavely and others (1976a, b, c) and Niem and Niem (1985), who also point out problems with defining the subsurface extent of the units. To calculate the area and volume of these invasive units requires simplifying approximations that estimate the volume of the invasive bodies from available data and convert them into equivalent volumes represented by a horizontal slab. Such approximations add uncertainty that must be taken into account.

Another problem is the possibility of undiscovered or missing CRBG units in the northern Coast Range of Oregon. Beeson and others (1979, 1985, this volume) postulated that the isolated exposures of Grande Ronde Basalt and Frenchman Springs Member flows along the north-central Oregon coast (Fig. 2) reached these areas via a pathway across the northern Oregon

Coast Range. Beeson and others (1985, this volume) presented evidence that major intracanyon flow complexes in the Willamette Valley, Oregon, trend toward the CRBG exposures on the coast and that the units involved in these intracanyon complexes are the same as those present on the coast. Although no CRBG exposures have been found within the Oregon Coast Range, the circumstantial evidence in the Willamette Valley suggests the existence of such a pathway. Based on several possible routes, we estimate the area of this pathway would be 500 to 900 km^2, and the potential volume of basalt might range from 70 to 200 km^3, only a small fraction of the total volume of the CRBG.

A potentially more significant question is that of the offshore extent and volume of the CRBG. Presently, insufficient data exists to define accurately the extent and thickness of CRBG units on the Oregon and Washington continental shelf. This paucity of data precludes us from including the submarine extension of the CRBG in the area and volume estimates. We speculate that the overall area and volume of the offshore CRBG may be similar to that onshore in the coastal areas. If so, the approximate offshore extent of the CRBG would be 4,000 to 7,000 km^2 and could potentially have a volume on the order of 1,000 to 3,000 km^3.

The final factor to be considered is the uncertainty introduced by the methods employed to calculate the areas and volumes. Such uncertainties would be errors produced when the distribution maps were digitized and problems within the program used to calculate the area and volume of the units.

Operator errors produced when the distribution maps were digitized would likely be random in nature and be manifested as very small deviations from the original rendition of the unit outline. Even if all such errors were additive, they would not affect the overall area much. The uncertainties associated with originally establishing the margins of these units, as discussed above, far exceed those that might reasonably be introduced during the digitizing process.

The last source of error is the uncertainty (accuracy) associated with the program subroutine used to calculate the area and volume of the units. A small degree of uncertainty is introduced by this process, but it is directly related to the complexity of the unit polygon. Even with the most complex polygons, we estimate that the amount of error could range from 0.01 volume percent to a maximum of less than 2 volume percent. Such error has been factored into the values presented in the second category in Table 4.

Based on this analysis, the overall estimates of the areal extent for the CRBG has a ±3 percent (5,000 km^2) level of uncertainty (Table 4). This level of uncertainty reflects the fact

TABLE 4. AMOUNT OF POTENTIAL UNCERTAINTY IN NEW AREA AND VOLUME ESTIMATES FOR THE THREE LARGEST CRBG FORMATIONS

	Uncertainty in Defining Unit Distribution		Uncertainty in Thickness Data/Isopach Map		Potential Total Change in Unit Volume (km^3)
	Potential Error in Area Estimate (km^3)	Potential Change in Unit Volume (km^3)* resulting from Area Estimate Error	Potential Error (%)	Volume Equivalent (km^3)	
WANAPUM BASALT					
Priest Rapids Member	± 500	± 15 (30 m)	10	± 280	± 295
Roza Member	± 500	± 15 (30 m)	10	± 130	± 145
Fenchman Springs Member	± 1,000	± 61 (61 m)	10	± 641	± 702
GRANDE RONDE BASALT					
N_2 Unit	± 1,000	± 91 (91 m)	10	± 2,790	± 2,881
R_2 Unit	± 1,000	± 152 (152 m)	15	± 7,965	± 8,117
N_1 Unit	± 5,000	± 610 (122 m)	20	± 6,280	± 6,890
R_1 Unit	± 8,000	± 976 (122 m)	25	± 9,050	± 10,026
IMNAHA BASALT	± 5,000	± 760 (152 m)	20	± 1,160	± 1,920
CRBG	± 5,000	± 2,680		± 28,296	± 30,976

*Volume derived from multipling the area by the average thickness of unit (in parantheses) as determined from the isopach map.

that the margin of the CRBG is, in general, well defined, even though the margins of some of its individual units are not (e.g., R_1 Grande Ronde Basalt; Table 4). The total volume estimate for the CRBG has a ±18 percent (31,000 km^3) level of uncertainty (Table 4). As summarized in Table 4, this value takes into account potential errors in estimating the volume resulting from changes in the areal extent of units, uncertainty in construction of the isopach maps, and the uncertainties introduced in the calculation of the volume of the units.

Volume of flows

Since the late 1960s, data available on some CRBG flows have been sufficient to allow estimates to be made of their physical size (e.g., Schmincke, 1967—Umatilla, Pomona and Elephant Mountain flows; Swanson and others, 1975—Roza and Ice Harbor flows; Swanson and Wright, 1978—Frenchman Springs, Priest Rapids, and Elephant Mountain flows; Mangan and others, 1986—Grande Ronde flows). Such estimates not only provide us with a better grasp of the physical size of CRBG flows but also serve as useful constraints on the modeling of potential rates of lava production along CRBG vent systems (e.g., Swanson and others, 1975; Mangan and others, 1986), duration of such eruptive activity and flow-emplacement periods (e.g., Shaw and Swanson, 1970a, b; Reidel and Fecht, 1987), and potential rates of magma generation and length of storage time (e.g., Hooper, 1984; Reidel and Fecht, 1987). Useful as they may be, such estimates have not been made for most CRBG flows due to insufficient data. Our new area and volume estimates present an opportunity to approach this problem from an alternative direction.

Our new values, along with available estimates of the number of flows within CRBG units, have been used to calculate the "average" volume per flow for the various CRBG units (Table 3). Obviously these estimates are in no way a true median value, and the actual volume of individual flows within a given unit could vary greatly above or below such values. These "average" flow-volume values are important, however, because they provide a method to appraise and establish the potential volumes of flows within the different CRBG units.

Based on these calculations, the "average" volume of flows within CRBG units is variable, ranging from less than 1 km^3 to more than 2,000 km^3 (Table 3). At the formational level, individual flow volumes range from about 39 to more than 1,200 km^3. In view of the disparity in the average flow volume between the five formations (Table 3), the single average volume of 561 km^3 per flow for the entire CRBG has questionable value. The volumes indicate that eruptive episodes that gave rise to the most voluminous formations (i.e., Grande Ronde and Wanapum Basalts; Figs. 4 and 5) were capable of repeatedly producing flows of thousands of cubic kilometers in volume, which we here term "great flows." These new volumes are one to two orders of magnitude greater than earlier speculations that typical CRBG flows might have volumes on the order of several tens of cubic kilometers (Swanson and Wright, 1978), but are within the range of volumes for Grande Ronde flows suggested by Mangan and others (1986).

It appears that the largest great flows probably exceed several thousand cubic kilometers in volume. Support for this contention comes not only from the averages in Table 3, but from direct calculation of the volume of selected flows within the Frenchman Springs and Priest Rapids Members (Wanapum Basalt) and Grande Ronde Basalt. One example is the oldest flow (Rosalia flow) in the Priest Rapids Member (Wanapum Basalt). The Rosalia flow is found throughout much of the extent of the Priest Rapids Member (Griggs, 1976; the authors, unpublished mapping and data). We estimate the volume of the Rosalia flow to be approximately 1,900 km^3, probably the largest great flow of post-Grande Ronde age. Great flows of even larger volume (exceeding 2,000 km^3) have been suggested within the N_2 magnetostratigraphic unit of the Grande Ronde Basalt (Umtanum flow; Reidel and others, this volume). However, given the tremendous extent and thickness of Grande Ronde units, some great flows could approach 3,000 km^3 in volume.

Constraints on the eruption and emplacement of great flows

Previous field, geochemical, experimental, and theoretical studies have provided estimates and constraints on the duration and magnitude of eruptive activity that produced CRBG flows (Shaw and Swanson, 1970a, b; Helz, 1978; Swanson and others, 1975; Swanson and Wright, 1981; Hooper, 1982, 1984; Mangan and others, 1986; Reidel and Fecht, 1987; Hooper and Swanson, 1987; Wright and others, 1989). Estimates and constraints derived from these studies were generally based on flows that ranged from 10 to 700 km^3 in volume; flows exceeding 1,000 km^3 in volume (great flows) were only rarely acknowledged (Mangan and others, 1986; Wright and others, 1989). Given the apparent significance of great flows within the CRBG, it is important to develop some parameters to gauge the magnitude of the eruptive activity that gave rise to such flows.

The first aspect that needs to be considered is the overall dimensions of the fissure systems that produced great flows. Most of the fissure systems that fed great flows are poorly exposed, and their dimensions cannot be determined accurately. However, limited field data and distribution patterns for great flows suggest they had fissure systems comparable in size (70 to 200 km in length) to better-documented CRBG fissure systems (Swanson and others, 1975; Hooper and Swanson, 1987; Wright and others, 1989). We therefore assume that fissure systems that fed great flows were not extraordinary in size by CRBG standards.

Previous studies (Shaw and Swanson, 1970a; Swanson and others, 1975; Mangan and others, 1986; Reidel and Fecht, 1987; Wright and others, 1989) indicate rapid eruption and emplacement rates, on the order of a few days to little more than a week or two, for CRBG flows. Available evidence suggests that emplacement time for great flows did not exceed the range of past estimates. We therefore conclude that great flows were not em-

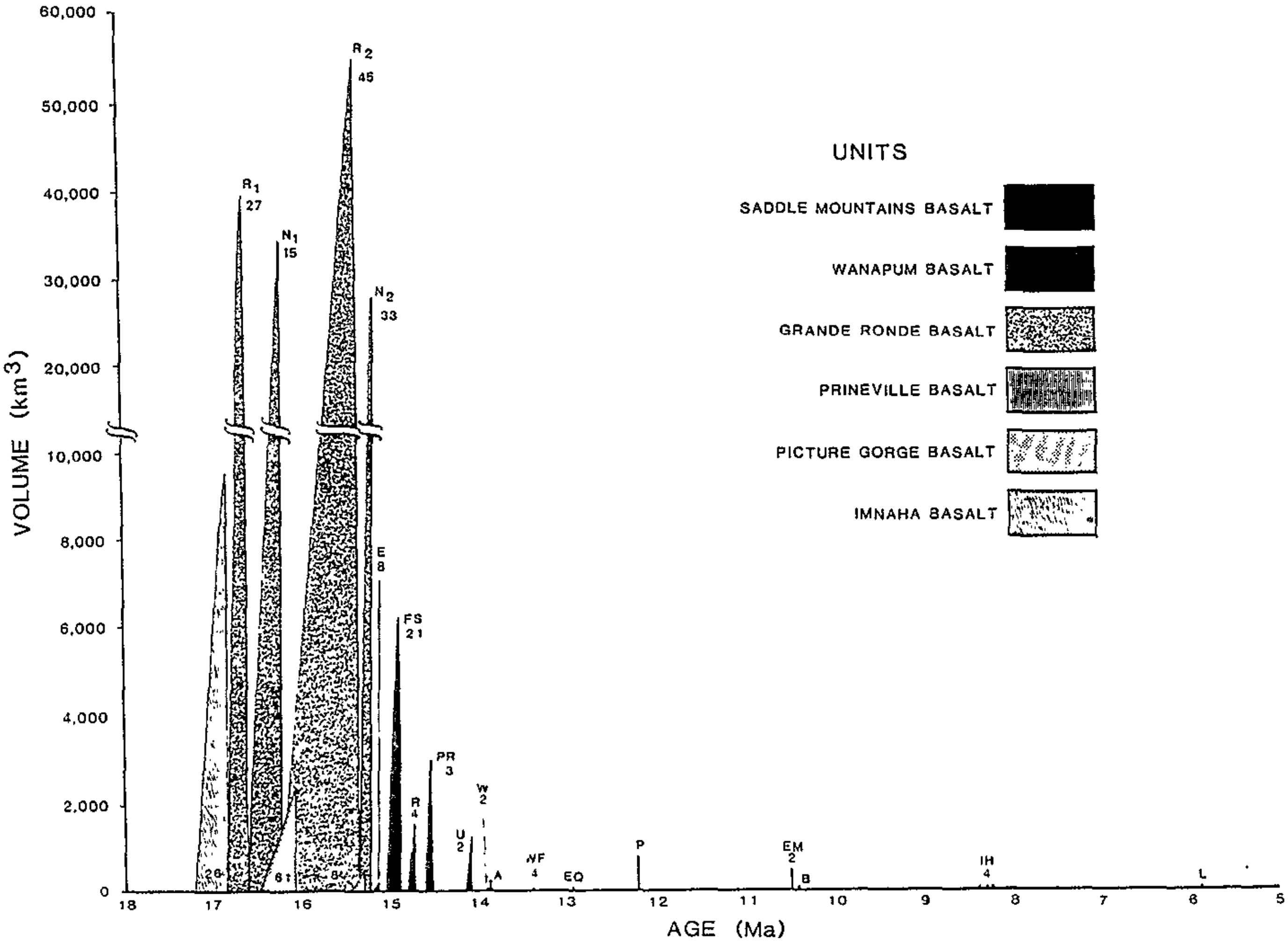

Figure 5. Plot showing the emplacement history for CRBG units based on new volume estimates (Table 3). Emplacement history of units composed of multiple flows (e.g., Imnaha Basalt) depicted by triangle whose apex represents total erupted volume. Base of the triangle represents duration of eruptive activity, estimated from isotopic dates. Note change of scale for volume. Members with only one flow (e.g., Pomona Member) are represented by single line. Letter(s) designate following units: E, Eckler Mountain Member; FS, Frenchman Springs Member; R, Roza Member; PR, Priest Rapids Member; U, Umatilla Member; W, Wilbur Creek Member; A, Asotin Member; WF, Weissenfels Ridge Member; EQ, Esquatzel Member; P, Pomona Member; EM, Elephant Mountain Member; B, Buford Member; IH, Ice Harbor Member; L, Lower Monumental Member. Number next to unit indicates number of flows; absence of number denotes that unit has only one flow. Individual flow ages, and duration of eruptive activity for units containing multiple flows, attempt to reconcile isotopic dates and flow paleomagnetic polarity to Miocene geomagnetic polarity time scale (Berggren and others, 1985). Existing geochronologic data and magnetic polarity data for the CRBG are insufficient to arrive at a unique calibration.

placed over an extended period and did not simply result from a longer period of eruptive activity.

If the above conclusions are correct, it suggests that the average rate of eruption (discharge) per unit time must have been significantly faster to produce great flows than for smaller (10^1 to 10^2 km^3) flows. Past studies suggest that to rapidly emplace flows of 10 to 700 km^3 would require average eruption rates on the order of 0.01 to 1 km^3/day per linear kilometer of fissure system (Shaw and Swanson, 1970a; Swanson and others, 1975; Swanson and Wright, 1981; Wright and others, 1989). Our calculations suggest that average eruption rates of 1 to 3 km^3/day per linear kilometer of fissure system would be needed to rapidly erupt the volume of lava contained within a great flow.

Such fast rates obviously imply the presence of a huge volume of magma and the necessary "plumbing system" for delivering the magma to the surface quickly to produce great flows. Such conditions must have prevailed during the peak period of CRBG eruptive activity (Grande Ronde time; Fig. 5) when great flows were repeatedly produced. However, the virtual cessation of the eruption of great flows by Saddle Mountains time (Fig. 5 and Table 3) implies that major changes occurred in either magma availability and/or the plumbing system. The reasons for this decline in production of great flows remain uncertain, but are probably related to changes in the fundamental process that gave rise to the CRBG.

SUMMARY

Previous estimates of the area (200,000 km^2) and volume (325,000 to 382,000 km^3) for the CRBG have been proved to be too large. The problem began when early volume and area estimates were linked with the wrong CRBG distribution map.

Based on available data, we have produced area and volume estimates for 38 stratigraphic units (Fig. 2 and Table 3) belonging to the CRBG. Although our compilation of these units has expanded the extent of the CRBG compared to past portrayals, our CRBG area-extent estimate, 163,700 km^2, represents a reduction of 18 percent compared to past estimates. Our estimate of the volume of the CRBG, 174,300 km^3, represents a reduction of as much as 50 percent compared to previous estimates. The amount of uncertainty within these estimates is ± 3 percent and ± 18 percent, respectively.

Results of our work indicate that CRBG eruptive activity produced flows ranging from less than 1 km^3 to greater than 2,000 km^3 in volume. During the peak period of CRBG eruptive activity (Grande Ronde time; Fig. 5), flows exceeding 1,000 km^3 (here termed "great flows") were commonly produced. Data suggest that some great flows could approach 3,000 km^3 in volume. These extensive and voluminous great flows qualify as the largest known terrestrial lava flows and even rival some pyroclastic flow deposits in size (e.g., ignimbrite sheets, Fisher and Schmincke, 1984). Whether other flood-basalt provinces produced flows of similar extent and volume is not known, but is crucial in evaluating the potential global impact of flood-basalt eruptions.

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